CHARACTERIZATION OF MAGNETOACOUSTIC EMISSION

RELATED TO STRUCTURAL PROPERTIES OF FERROMAGNETS

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INTRODUCTION

An extensive study of magnetoacoustic emission (MAE) properties has been performed over the past several years[1, 2]. As a result, the dependence of the spectral characteristics of MAE on certain microstructural variations and uniaxially applied stress in a particular type of low carbon steel are now well known. The embrittlement-causing concentration of certain atomic species, e. g., tin, sulphur, phosphorous etc.[3], at the grain boundaries of this steel creates strong potential barriers resisting the motion of non-180° domain walls which is the source of MAE. (Since the only type of non-180° domain walls in this material are 90° domain walls, the term 90° domain wall will be used throughout this paper in place of non-180° domain wall.) An MAE burst produced during one-half cycle of a hysteresis loop at a low AC magnetic field frequency (e. g., 0.7 Hz) shows two sub-peaks; the leading peak is usually sharp and short-lived, while the trailing peak is usually smooth and long-lasting. It has been shown that the enhanced domain wall-defect interaction, due to the strengthened potential barriers, causes an increase in the asymmetry of the MAE signal by suppressing the leading sub-peak and amplifying the trailing sub-peak[4]. This phenomena is due to the delayed motion of the 90° domain walls. The effect of a tensile stress applied parallel to the external AC magnetic field is to diminish the MAE. On the other hand, the amplitude of the MAE burst has been shown to be a non-monotonic function of the stress amplitude[5]. Recently, our study has concentrated on obtaining quantitative values for parameters computed from the MAE spectra averaged over a sufficient number of cycles to achieve statistical stability. Nevertheless, certain fundamental elements of the MAE characteristics remain unexplained.

Monitoring the maximum rate of change in the net magnetic induction in the test sample, $|\partial\phi/\partial t|$, through the pickup coil output, it has been observed that the region that should have the most active domain wall motion corresponds to the lowest MAE activity. The leading peak appears far earlier than the maximum of $|\partial\phi/\partial t|$ and the trailing peak lasts long after the change in magnetic induction ends. The cause of this phenomenon has not been fully explained. In the past, our investigations have used only a single sample geometry to study the effects of embrittlement and uniaxial stress on MAE. This was done to isolate the material property effects on the MAE characteristics from the sample geometry-dependent effects. Further investigations are now necessary to determine whether or not the peculiarity in the phase relation between the MAE spectrum and pickup coil output is unique to certain sample geometries. In addition, it is also desirable to study the MAE characteristics of the samples when their thicknesses are less than or equal to the skin depth of the material. Earlier studies used samples that were 12.5 mm (0.5 in.) thick. A drive frequency of 0.7 Hz corresponds to a skin depth of approximately 5 mm (0.2 in.) for the samples used in this study.

EXPERIMENTAL

Two sets of test samples were prepared for the present study. The first set was made of polycrystalline pure iron with a nominal purity of 99.999% and the second set of samples were made from the same untreated steel used in the previous studies. All the samples had the same rectangular cross-section of 6 x 1.5 cm^2, but were of different thicknesses. Each set consisted of three samples with the following thicknesses; 0.5, 1.25 and 2.5 mm. The pure iron samples were assumed to have been rolled to different degrees during the manufacturing process and, hence, have somewhat different microstructures. This is why a parallel study with another set of samples was necessary. The steel samples used in this study have been cut from a section of a cast block and then machined to the proper thickness. As a result, there should be virtually no variation in the microstructure among these samples. For the present study the frequency of the applied AC magnetic field was kept at 0.7 Hz and the amplitude of surface magnetic field was kept at H_x = 640 Oe. The MAE data were first digitized and then rectified. To obtain statistical stability the MAE spectrum was averaged over 50 one-half cycles of the hysteresis loop. Other details of the experimental system can be found elsewhere[1,4,5]. To add supporting information for the interpretation of the results a series of hysteresis loop measurements were performed using a Helmholtz pair where the amplitude of the magnetic field was monitored by a Hall probe gaussmeter and the magnetic induction in the sample was measured by using an integrating fluxmeter.

RESULTS AND DISCUSSION

Fig. 1 shows the results of the 0.5 mm thick pure iron sample, the upper scope trace is the pickup coil output for one-half cycle of the hysteresis loop and the lower trace is that of the corresponding MAE spectrum. These results clearly show that the sharp leading subpeak of the MAE burst occurs far earlier than when the major change in the magnetic state takes place whereas very low MAE activity occurs in the region where the magnetic activity is highest. The motion of 90° domain walls always lags behind that of 180° domain walls and the major change in the net magnetization is due to the motion of 180° domain walls. Since the main source of the MAE generation is due to the motion of 90° domain walls, one can argue that the MAE activity should appear after the peak in the pickup coil output. The location of the leading MAE peak, however, cannot be explained by this argument. Hence, a new mechanism is necessary to provide a consistent explanation of the phenomena. Another

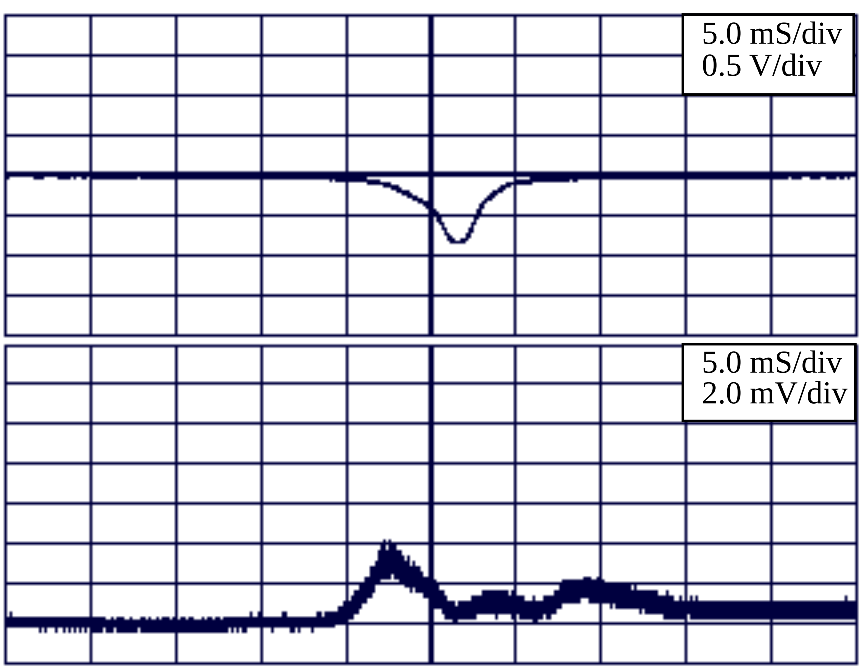

Fig. 1. Results obtained with the 0.5 mm thick pure iron sample.

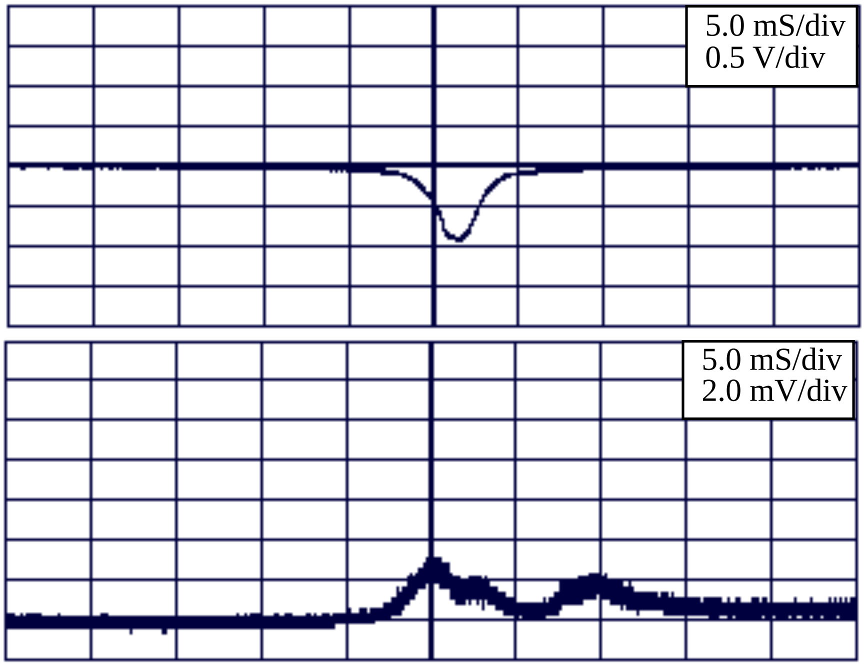

Fig. 2. Results obtained with the 0.5 mm thick steel sample.

interesting spectral characteristic shown in this figure is the presence of a three-peak structure which was not observed during previous tests with thick steel samples. Fig. 2 shows data obtained with a 0.5 mm thick steel sample. The results show the same qualitative features seen for the iron sample including the three-peak structure in the MAE burst.

The results obtained with the 1.25 mm thick pure iron and steel samples are shown in Fig. 3 and Fig. 4, respectively. The presence of the three-peak structure in the MAE burst is even more pronounced in these samples compared to the thinner samples shown in Figs. 1 and 2. The features that are clearly different from the results of the two thinner samples are the increased peak amplitude and width of both the pickup coil output and MAE burst. Otherwise, the early appearance of the leading MAE peak and late appearance of the trailing peaks in reference to the position of the peak in the pickup coil output remains unchanged.

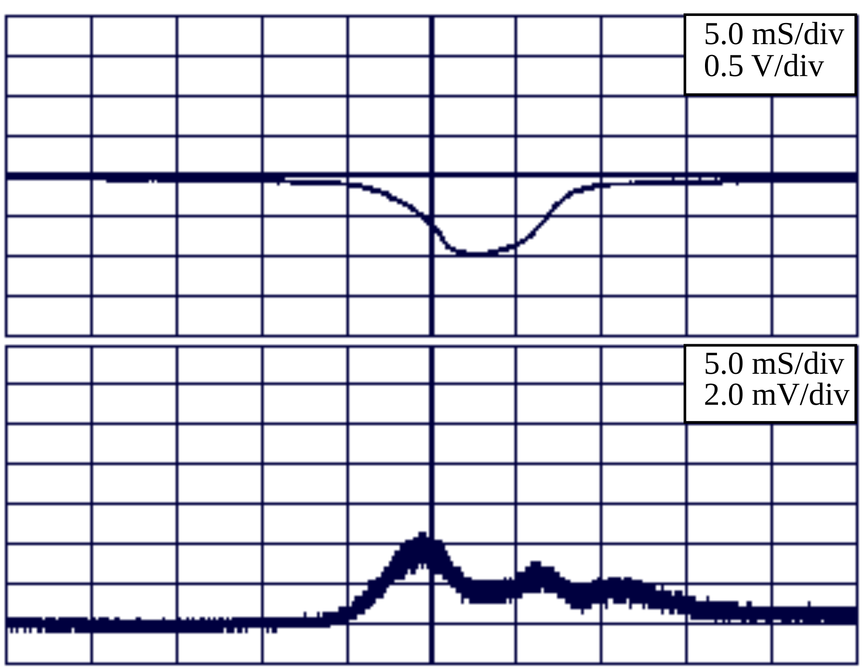

Fig.3. Results obtained with the 1.25 mm thick pure iron sample.

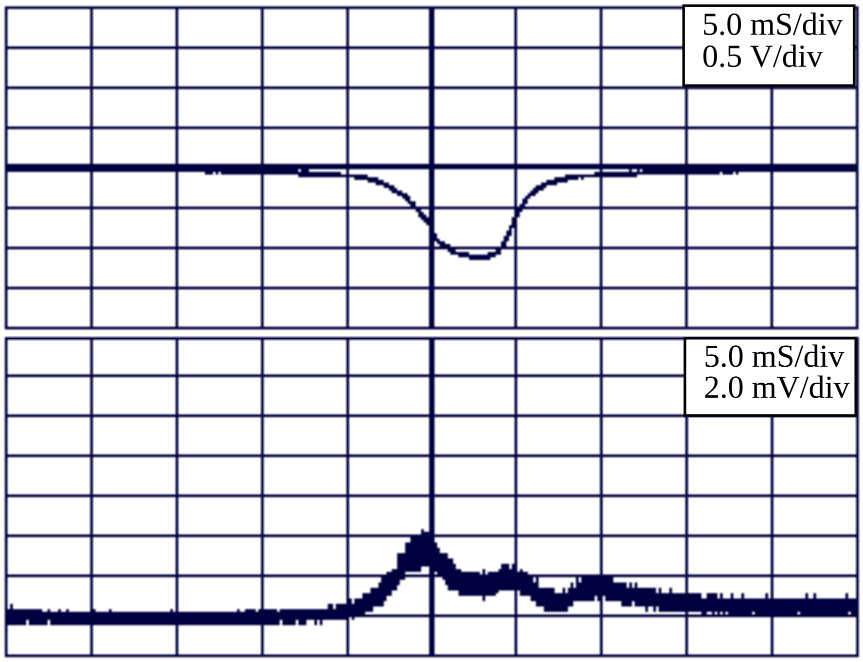

Fig. 4. Results obtained with the 1.25 mm thick steel sample.

The next two figures show the results obtained with the remaining two sample which are 2.5 mm thick. A complete disappearance of the three-peak structure in the MAE burst is observed for the pure iron sample as shown in Fig. 5. In contrast to the results of the previous figures, the peak amplitude of the trailing peak is comparable to that of the leading peak for the pure iron sample. In the case of the steel sample, as shown in Fig. 6, the tendency of the disappearing three-peak structure is clear, but both the pickup coil output and the MAE burst are not as symmetric as those shown for the pure iron sample in Fig. 5. Another common feature between the results of these two samples is that the maximum of the pickup coil output no longer shows a peak, but instead forms an extended region which is much different from those observed for the thinner samples of both types.

Apparently, the early appearance of the leading MAE peak is a characteristic which is common to all the results observed in the present study and needs to be explained in terms

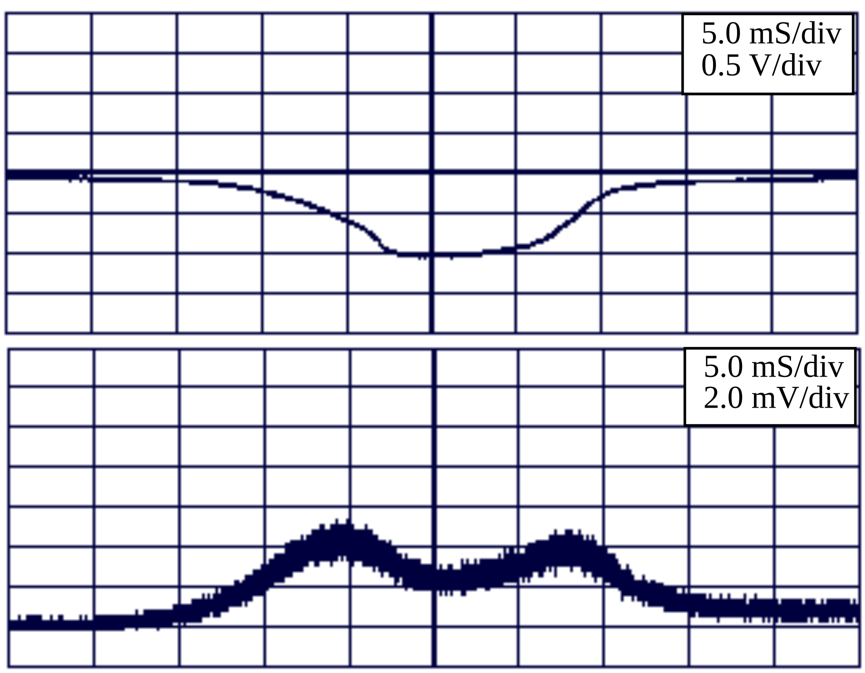

Fig. 5. Results obtained with the 2.5 mm thick pure iron sample.

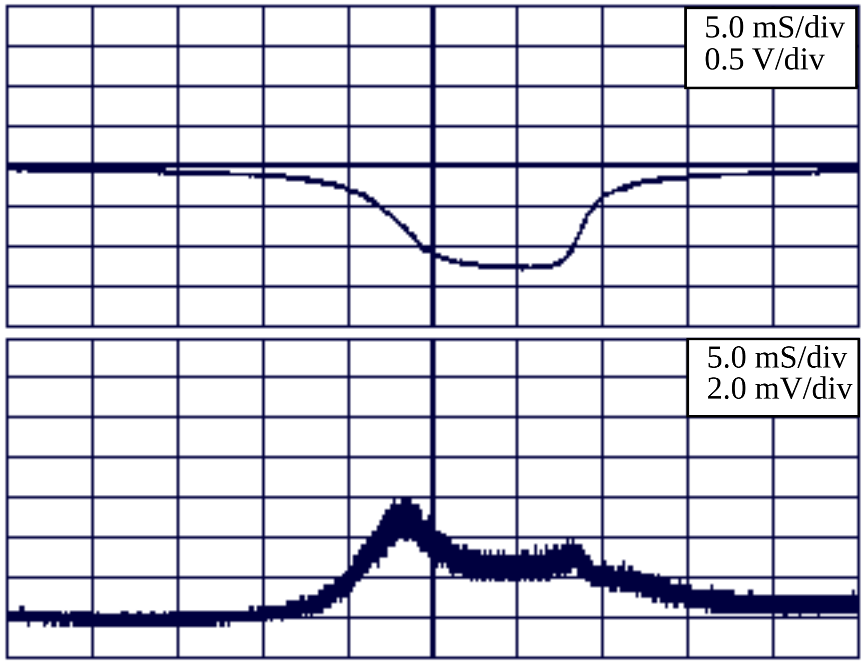

Fig. 6. Results obtained with the 2.5 mm thick steel sample.

of general properties of ferromagnets. Once a specimen is saturated along one direction, it is not possible to bring the saturated state into another direction without having seed domains of reverse magnetization. This means that no saturated state is perfect, which actually is a consequence of the fact that no specimen is perfect. It is Bloch who first put forth the idea of the existence of a closure domain structure forming spike-like domains in the vicinity of nonmagnetic inclusions in a ferrimagnet. The total magnetostatic energy associated with the free poles at the surfaces of 90°-like domain walls enclosing the spike domains is lower than the energy associated with the free poles created at the surface of nonmagnetic inclusions. Such a prediction made by Bloch was based on a theoretical analysis and soon after its existence was experimentally verified by Schokely et. al.[6]

Fig. 7 schematically illustrates the process of nucleation and expansion of the domains of reverse magnetization in the vicinity of a nonmagnetic inclusion. In the saturated state the presence of the spike domain contributes to the formation of closure domains as in Fig. 7 (a). As the strength of the external magnetic field that maintained the saturated state of (a) begins to decrease, the spike domains tend to rotate and the magnetization vectors inside these domains reorient themselves until they are antiparallel to the net magnetization of the specimen. They finally reach a point where the domains of reverse magnetization are as shown in Fig. 7 (c). With a further decrease in the applied magnetic field these regions of reverse magnetization rapidly grow and cause a sudden increase in the area of 90° domain walls thereby generating MAE activity.

A thorough theoretical analysis on the formation of the reverse magnetization domains was made by Goodenough[7] which includes the contribution of nonmagnetic inclusions and grain boundaries of a polycrystalline ferromagnet. For the analysis of the present results we will follow the treatment given by Goodenough. We define H_{ni} as the critical magnetic field strength for the nucleation of the seed domain of reverse magnetization in i_{th} region in the specimen. H_{ni} is defined to be positive if its direction is parallel to that of magnetization within the seed domain and, otherwise, it is defined to be negative. If H_{ni} is positive for all the regions in the specimen the difference in the magnetic induction between the saturation and remanence is solely due to domain rotation and the pattern of the hysteresis loop in the first quadrant should resemble a sharp spike aligned along the positive H-axis. On the other hand, if H_{ni} is negative for the majority of the regions in the specimen, the upper line of the hysteresis loop in the first quadrant should be a curve formed by rapidly decreasing induction when approaching the remanence. Whether or not such a closure domain should form at a particular nonmagnetic inclusion solely depends on its size as it determines the total magnetostatic energy associated with the demagetization field which can be easily shown to be:

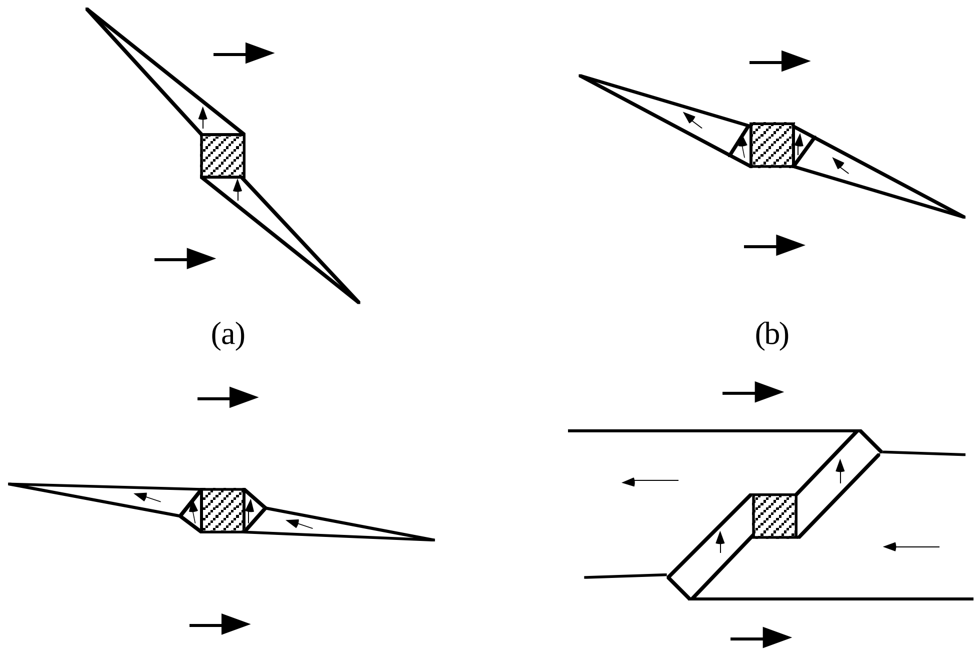

Fig. 7. (a). Closure domain structure in the vicinity of a nonmagnetic inclusion, (b). Rotation of spike domains and reorientation of the magnetization in these domains upon the decrease in the applied field strength, (c). Nucleation of seed domains of reverse magnetization and (d). Expansion of domains of reverse magnetization suddenly increasing the area of the 90^{o} domain walls thereby creating a burst of MAE.

$$-\frac{1}{2}\int \vec{H}_d \cdot \vec{I}_s dv = \left(\frac{8\pi^2}{9}\right) I_s^2 R^2$$

where $\vec{H}_d$ is the demagnetization field, $\vec{I}_s$ is the saturation magnetization and R is the radius of the inclusion when approximated as a sphere. The magnetostatic energy of the closure domains shown in Fig. 7 (a), when approximated as a prolate ellipsoid, can be written as:

$$E_c = \frac{\pi^2 R^2}{2\lambda}\sigma_w + \frac{16\pi^2\eta}{3\sqrt{2}}\lambda\left[ln\left(\frac{2}{\lambda}\right) - 1\right] I_s^2 R^3 - 2H_n I_s \frac{2\pi R^3}{3\lambda\sqrt{2}}\cos\theta$$

where σ_w is the domain wall energy density, θ is the angle between the magnetization and the applied field, λ is the ratio of the semi-minor to semi-major axes of the ellipsoid and η is a correction factor first introduced by Williams et. al[8] for the compensation necessary due to the finite anisotropy energy. From the above two expressions, one can derive the critical field strength for the creation of the seed domains of reverse magnetization in the vicinity of a nonmagnetic inclusion as:

$$H_n = \left\{\frac{9}{16}\left(\frac{\sigma_w}{RI_s^2}\right) + 3\sqrt{2}\lambda^2\eta\,[ln(2/\lambda) - \lambda]\right\}\frac{2\sqrt{2}\pi}{3\cos\theta} I_s$$

Assuming that $\lambda \approx 30$ and $\eta = 0.1$, it becomes

$$H_n \approx \left[1.7\left(\frac{\sigma_w}{RI_s^2}\right) - 0.18\right] I_s$$

In iron if $R>10^{-5}$ cm, the above equation gives $H_n<-10$ Oe, which means that the presence of nonmagnetic inclusions with a size comparable to 10^{-5} cm causes the formation of domains of reverse magnetization long before the magnetic state reaches the remanence.

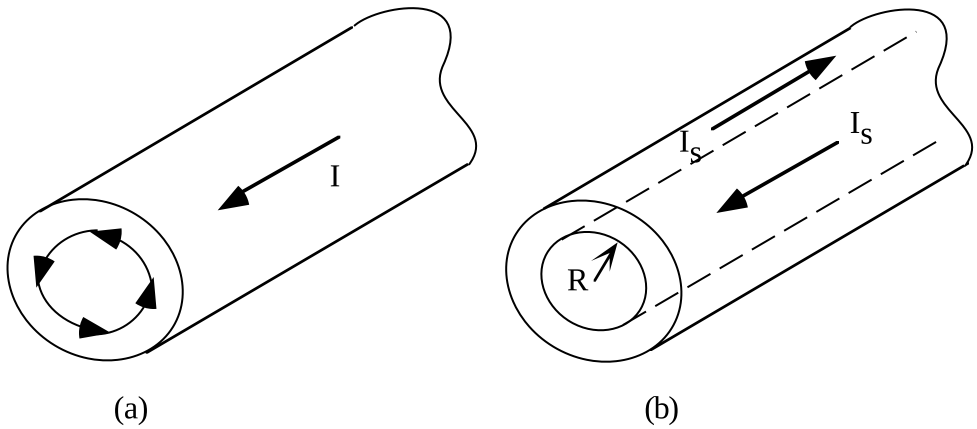

Fig. 8. Schematic illustrations of dynamic change in magnetic induction which occurs (a). gradually over the cross-section and (b). abruptly across the 180^o domain wall.

Despite the high purity of the iron samples, they still appear to possess enough nonmagnetic inclusions so that the generation of the leading MAE peak occurs considerably earlier than the major domain wall motion that causes the peak in the pickup coil output. Separate measurements of the hysteresis loops and an analysis of optical micrographs of the samples clearly support the above assumption [9].

The fact that the MAE activity level becomes low as the pickup coil output reaches its maximum needs to be analyzed from a dynamical point of view due to the rapid change in the magnetic state. It was well known that the eddy current loss which is calculated using the assumption of a gradually varying magnetic induction across the cross-section of the ferromagnetic core, as schematically illustrated in Fig. 8. (a), is always smaller then the actually observed value by a factor of 2 or 3 [10]. Through their widely known experiment with a single crystal iron picture frame sample, Williams et. al proved that a dynamical change in the magnetic state is due to the motion of 180° domain walls. This means that the whole specimen is divided into only two domains and a single 180° domain wall moves upon the application of an external magnetic field. Applying this idea to a cylindrical ferromagnetic rod as shown in Fig. 8. (b), one can obtain the value of eddy current loss which is much more realistic. Based on experiments, Williams et. al proved that with a small applied magnetic field the 180° domain wall moves preserving its original surface flatness. Upon the application of a large field the wall tends to move rapidly, but is resisted by the induced eddy current. As a result, the 180° domain wall is bent and its movement is partially delayed.

The magnetic domain structure in a polycrystalline specimen undergoing a dynamic change is more complicated than that illustrated in Fig. 8 (b) due to the presence of 90° domain walls. Nevertheless, applying the idea of a 180° domain wall moving from the outer surface of the specimen into the center region with a finite speed, one can clearly see the origin of the thickness dependence of the width of the pickup coil output as shown in Figs. 1 to 6. The mobility of 180° domain walls is known to be higher than that of 90° domain walls by a factor of about 50. Due to such a difference in the mobility, the 90° domain walls tend to delay the motion of 180° domain walls. The logical explanation of the low MAE activity in the region of high pickup coil output is that during the major change in the magnet induction by the motion of the180° domain walls, as in Fig. 8. (b), the 90° domain walls stay behind and the 180° domain is bent to some degree due to the eddy currents. Past this stage, the 90° domain walls move in as the 180° domain wall collapses in the center of the cross-section of the specimen. The motion of these two types of magnetic domains occur after the major motion of the 180° domain wall, creating the long-lasting MAE sub-burst(s). Utilizing the dynamics involved in the change in the magnetic state, all the major elements of experimentally observed characteristics are explainable except the presence of the three-peak structure observed only in the two thinner samples.

SUMMARY

A series of MAE experiments was performed using sets of pure iron and low carbon steel samples with three different thicknesses. The appearance of the leading sub-peak of the MAE in the initial stage of reducing the magnetic induction from the saturated state was proved to be universal. Such an early appearance was explained in terms of the nucleation of the seed domains of reverse magnetization and follow-on expansion of these domains before the reversal of the applied magnetic field. The low MAE activity in the region of high pickup coil output was also shown to be a universal characteristic which was explained based on the dynamics of the 180° domain wall that divides the specimen into two domains. The low mobility of 90° domain walls, which are responsible for the generation of MAE, and the delayed motion of the 180° domain wall due to eddy currents can explain the extended range of the MAE activity after the leading peak. The appearance of the three-peak structure in the two thinner samples, however, remains unexplained.

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